Considerations Regarding the Treatment of Launch Vehicle Flight Control Stability Margin Reductions with Emphasis on Slosh Dynamics

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Agenda

- **Stability Margins**
  - Industry-standard stability margin guidelines
- **Analysis to support flying with reduced stability margins**
  - Utility of flight data and time-domain analysis
  - Fundamental dynamics, sensitivities, and performance (slosh example)
  - Sensitivities and consequences (slosh example)
  - Flight control stabilization trades

Flight Control Stability Margin Industry Standards (1 of 2)

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Design, Development, Test, and Evaluation (DDT&E) Considerations for Safe and Reliable Human Rated Spacecraft Systems			Page #: 1 of 133

Volume I

Design Development Test and Evaluation (DDT&E) Considerations for Safe and Reliable Human Rated Spacecraft Systems

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GN&C Engineering Best Practices For Human-Rated Spacecraft Systems

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The NASA Engineering and Safety Center (NESC) recently completed an in-depth assessment to identify a comprehensive set of engineering considerations for the Design, Development, Test and Evaluation (DDT&E) of safe and reliable human-rated spacecraft systems. Reliability subject matter experts, discipline experts, and systems engineering experts were brought together to synthesize the current "best practices" both at the spacecraft system and subsystems levels. The objective of this paper is to summarize, for the larger Community of Practice, the initial set of Guidance, Navigation and Control (GN&C) engineering Best Practices as identified by this NESC assessment process.

I. Introduction

The NASA Engineering and Safety Center (NESC) is an independent technical resource that was formed in the wake of the Columbia tragedy to provide assessments of and recommendations to NASA programs on engineering and safety issues. A brief overview of the NESC organization along with a detailed portrayal of the operations of the NESC's GN&C Technical Discipline Team (TDT) is presented in Reference 1.

Recently the NESC completed an in-depth assessment to identify, define and document a comprehensive set of engineering considerations for the Design Development Test and Evaluation (DDT&E) of safe and reliable human-rated spacecraft systems. The Astronaut Office at NASA's Johnson Space Flight Center requested this NESC assessment. As part of this assessment NESC brought reliability subject matter, subsystem discipline, and systems engineering experts together to synthesize the current "Best Practices" that ensure robust, safe, and reliable critical human-rated spacecraft systems. The findings and recommendations resulting from this assessment are documented in Reference 2: Volume 1 of Reference 2 addresses the topic of spacecraft Systems Engineering for safety and reliability while Volume 2 of Reference 2 reports the subsystem-level findings and recommendations. The GN&C engineering Best Practices presented in this paper have been extracted and condensed from Section 7.5 of Volume 2 of Reference 2.

This paper will summarize the initial set of Guidance, Navigation and Control (GN&C) engineering Best Practices as identified by the NESC's GN&C TDT during this assessment process. These Best Practices address both the early and late phases of the overall DDT&E process. They cover a broad range from fundamental system architectural considerations to more specific aspects (e.g., mathematical modeling) of GN&C system design and development.

The motivation of this paper is to provide useful guidance, in the form of these Best Practices and other considerations and criteria, to the formulation, architecture, design, development and operation of GN&C systems for NASA's future human-rated spacecraft. It is sincerely hoped that engineers and managers can use this

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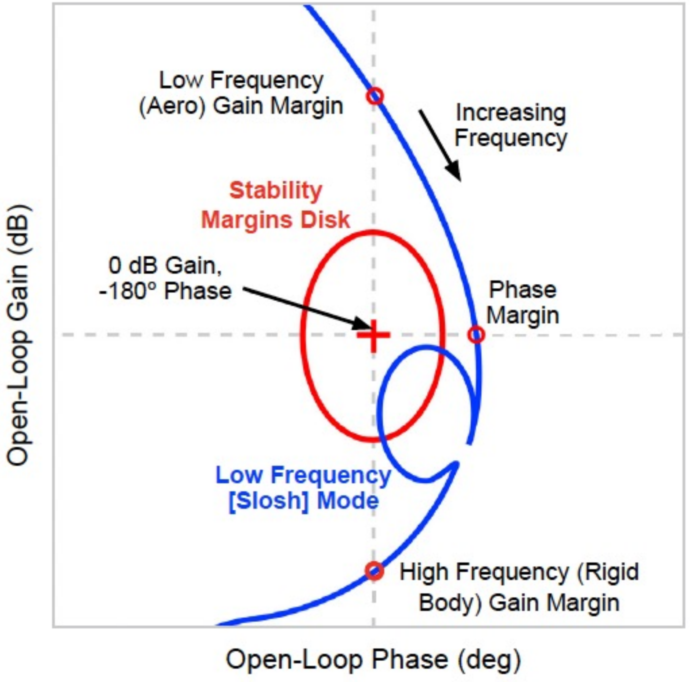
GN&C Best Practice #12

Stringent attention must be paid to stability considerations such as gain and phase margins, damping ratios, and the choice of gain or phase compensation techniques.

- **No NASA standard exists that addresses launch vehicle flight control requirements; however:**
  - The NESC published (in 2007) an assessment report, "**Design, Development, Test and Evaluation (DDT&E) Considerations for Safe and Reliable Human Rated Spacecraft Systems**," covering engineering best practices/guidelines for human-rated spacecraft
  - An AIAA paper, "**GN&C Engineering Best Practices for Human Rated Spacecraft Systems**," written by NESC GN&C TDT members, was subsequently published in 2007, summarizing the NESC assessment report
  - These industry standard guidelines for stability margins were adopted for the CCP 1140 guidelines
    - **CCT-STD-1140, Crew Transportation Technical Standards and Design Evaluation Criteria, Rev. B-1, April 8, 2015**
  - Goddard Space Flight Center Rules for the Design, Development, Verification, and Operation of Flight Systems (i.e., "**Goddard Gold Rules**") contain stability margins, but were not developed for use with human-rated launch vehicles

Flight Control Stability Margin Industry Standards (2 of 2)

- **<u>Undispersed</u> flight control system stability margins** in the open-loop transfer function
  - Rigid body gain/phase margins should meet or exceed **6 dB/30 degrees**
  - All gain-stabilized flexible body modes should meet or exceed 12 dB amplitude (gain) margin
  - Well-characterized fundamental (low-frequency) flexible body modes may be phase-stabilized to maintain 45-degree phase margins
- **<u>Dispersed</u> flight control system stability margins** in the open-loop transfer function
  - Rigid body gain/phase margins should meet or exceed 3 dB/20 degrees
  - All gain-stabilized flexible body modes should meet or exceed 6 dB amplitude (gain) margi
  - Well-characterized fundamental (low-frequency) flexible body modes may be phase stabilized to maintain 30-degree phase margin



<u>Remarks</u>

- **Launch vehicle flight control system stability analyses should include:**
  - All flexible body, slosh mode, and nozzle inertial coupling effects
  - All sampled-data and sensor/actuator latency effects
- **The stability analyses should evaluate system uncertainties, including frequency and damping of all modes, and consider flexible body mode shapes. Analysts should determine which dynamic coupling effects drive margins.**

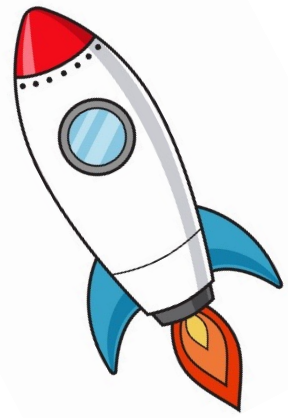
Accompanying Analysis for Reduced Stability Margins

- NESC's perspective for crewed spaceflight: **Flight control gain/phase stability margin reductions from industry standards can represent an acceptable balance in overall flight risk posture, but acceptance of departures should be accompanied by an adequately extensive technical treatment, including:**
  - Analyzing the **fundamental physics** involved, with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
  - Conducting **sensitivity studies** in time and frequency domains to analyze effects of possible parameter and system variations
  - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
  - **Assessing alternative flight control designs** to demonstrate that present design appropriately balances overall vehicle risk (i.e., quantitatively delineate chosen tradeoffs between various stability margins and vehicle performance in the context of risk/consequence)
- Proposed approach discussed in the context of reduced **slosh** margins

Utility of Flight Data in Validating Slosh Model/Stability Margins

Flight experience raises confidence, but does not necessarily validate models or stability margins

Flight data is typically inconclusive regarding slosh stability margins



- In-flight observation of slosh instability is known to be difficult
  - Adequate excitation source may not exist
  - Growth rates are small
  - Chaotic, aerodynamic disturbances modify or break limit cycle oscillations (LCO)
- Flight tests may not provide sufficient post-flight data to anchor slosh model predictions or extract and validate stability margins against guidelines
  - The lack of slosh response in flight is not a positive test for vehicle robustness
  - In the absence of targeted excitation with adequate persistency and sufficient sensing, specific vehicle model response validation (e.g., aero, rigid body, slosh or flex) is not possible
    - Recovery of slosh dynamics from flight data may not be possible with necessarily limited in-flight excitation
    - In-flight response of lightly damped modes (e.g., flex, slosh) can provide frequency confirmation if sufficient excitation exists. Very long excitation dwell times would be needed to identify slosh gain and phase margins.

Utility of Time Domain Analysis in Validating Stability Margins

- **Time domain analysis using a high-fidelity 6-DOF simulation, with or without targeted excitation, can confirm the expected response of slosh to demonstrate whether an observable response is likely**
  - Flight data may not reveal significant thrust vector control (TVC) response in the frequency spectrum of expected slosh dynamics
  - Slosh response may be clearly visible in spectrogram when slosh is excited, but absent without
- **Time-domain Monte Carlo analysis should be supplemented with a comprehensive treatment of offending dynamics:**
  - Analyzing the **fundamental physics** involved with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
  - Conducting **sensitivity studies** in time and frequency domain to analyze effects of possible parameter and system variations
  - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
    - Sensitivity studies aid in identifying parameter sets that most challenge the system stability so the associated consequences may be evaluated

Time domain responses alone, utilized in day-of-launch processes or otherwise, are not a sufficient means of addressing propensity for unstable conditions without a more comprehensive treatment of the offending dynamics.

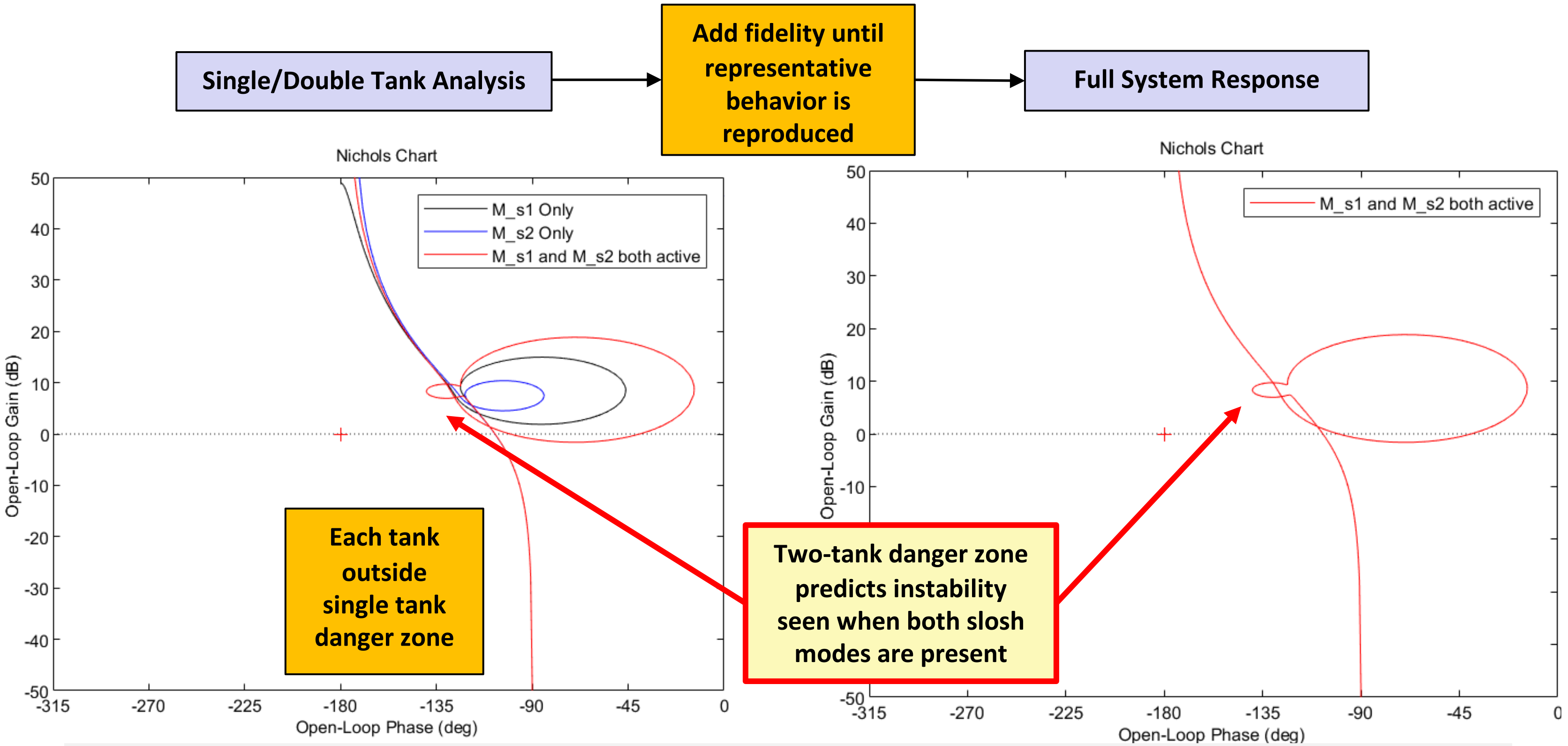
Fundamental Dynamics: Behavior Should be Verified with Simplest Model

Analysis of **fundamental physics** involved with applicable simulation tool verification is important if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data

- Fundamental physics can enable understanding and mitigation of apparent time/frequency discrepancy

- To ascertain fundamental physics:
  - Determine simplest physics model that matches the response of the full system model to develop an understanding of the driving dynamics
  - Add fidelity until sufficient matching to full system response

- <u>Example</u>: Slosh tanks exhibiting coupled behavior depart from expectations guided by classical single-tank criteria and can show instabilities when uncoupled tanks show stability.



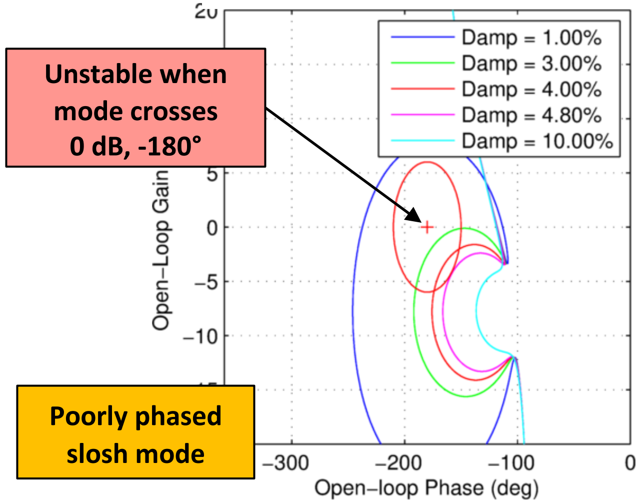
Simplified representation of launch vehicle two-tank physics slosh model formulated on first principles can reproduce the fundamental behavior seen in full system model

Figures c/o Jing Pei, "Analytical Investigation of Propellant Slosh Stability Boundary on A Space Vehicle," Journal of Spacecraft and rockets Sept-Oct 2021 Vol. 58, No. 5, and some contributions thereafter. Simplified models confirmed using basic proportional-derivative (PD) feedback, rigid body (RB) dynamics, and first slosh modes of each tank.

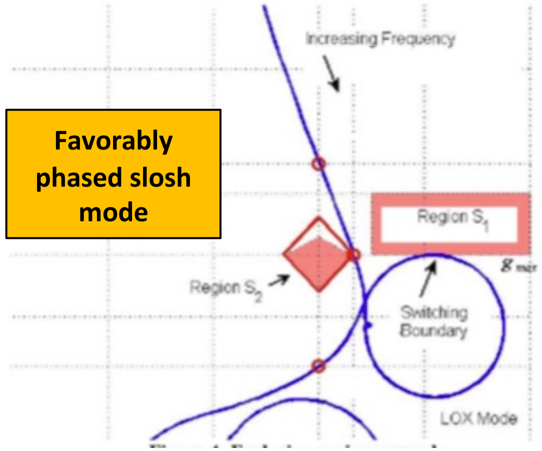
Fundamentals Dynamics: Slosh

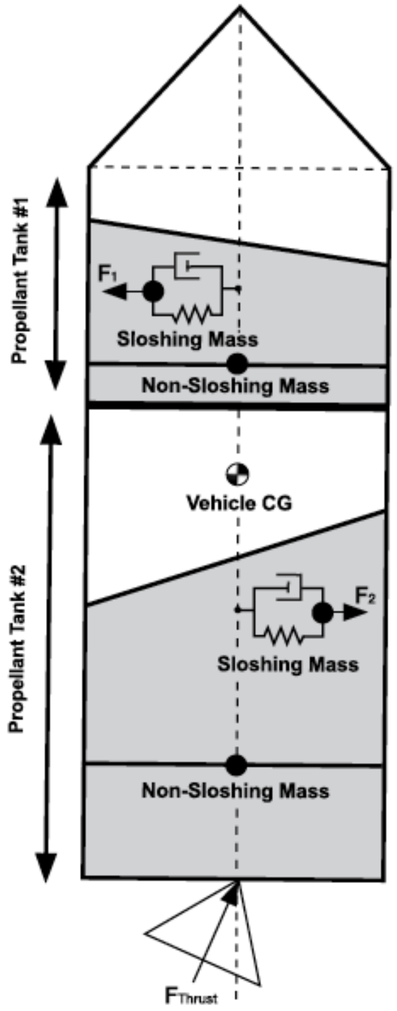
- **Slosh is commonly modeled as linear 2-D mass spring damper or 2-D pendulum**
  - Mechanical model parameters are scheduled vs. flight time (liquid level) and conditions (acceleration) and based on established empirical relationships
- **Long-established slosh "danger zone" criteria exists for *single* tank** *[Bauer 1963]*, **which can indicate propensity for vehicle control instability**
  - Poorly phased slosh modes fall aft of center of percussion and forward of the CG; also visible as margin encroachment on Nichols chart
  - Recent results show that the danger zone extends aft of the CG *[Ottander 2018]*
- **More complex slosh phenomena include interactions with multiple propellant tanks and structural dynamics (flex), which impact vehicle stability**

Nichols Example Poorly Phased



Nichols Example Favorably Phased





Evaluation of Sensitivities in Frequency-Domain

Dispersed stability analysis and targeted sensitivity studies can determine the propensity for impact on margins.

Sensitivities to investigate for propellant slosh include:

- **Vehicle flexibility**
  - Flex body dynamics can significantly impact phase margins
  - Flex body dynamics can reduce slosh margins or potentially destabilize a slosh mode
    - Impact of flex on time-domain slosh response characteristics may be modest
- **Relative slosh frequency**
  - Coupling effects between two tank slosh dynamics can be significantly influenced by relative slosh frequency
- **Actuator and sensor nonlinearities (details in backup)**
- **Rotary slosh (see backup)**
- **Autopilot filter, latency, and other source of phase lag**
  - May have destabilizing impact on poorly phased propellant slosh

Inclusion of flexible body dynamics can significantly reduce slosh phase margin due to dynamic coupling.

Two-tank coupled slosh behavior can be sensitive to relative frequency of the slosh modes.

Stiction in TVC actuators or equivalent effects can decouple the controller from propellant slosh effects (i.e., mask small-amplitude time-domain instabilities) during quiescent regions of flight until slosh amplitudes are large enough to induce motion.

Sensitivities and Consequences

Supplementary Analysis (Stressing Cases) in Time-Domain

Simulations

Simulate many possible opportunities for instability to occur in flight; once sensitivities are understood, evaluate whether they are credible/probable

Doublet (shuttle approach): Application of doublet(s) during periods of instability for (1) nominal system and (2) worst-case dispersed

- Multiple amplitudes: 0.5°, 1°, 1.5°, 2°, 3°
- Consider reasonableness of doublet amplitude

Direct Slosh Initialization: Initialize slosh states during periods of reduced margin for (1) nominal system and (2) worst-case dispersed

- Pure lateral (pitch, yaw, pitch/yaw)
- Pure rotary
- Attempt to cover the space in between
- Compare slosh amplitudes with what is seen from Monte Carlo simulation and intentional excitation via doublet analysis

Indicators

Indicators to consider with time-domain results:

- Observation of stability/instability
- Time to double/half
- Actuator usage
  - Amplitude
  - Rate (<10% capability?)
  - Impact to loads
- Slosh wave amplitude
  - Mechanical model breaks down
  - Loads
  - Thermal/fluid management (ullage collapse)
- Acceleration at crew location
- Abort margins

Supplementary analyses (i.e., stressing cases in the time domain) can determine if unanticipated stability concerns or sensitivities exist.

Evaluation of Flight Control Stabilization Trades

- **Clarify what constitutes an "optimal" design, given the complex trades between flight control filter/gain design, flex attenuation, slosh stability, rigid body phase margin, and aero margin**
- **Explore adjustments to the flight control system (FCS) parameters for a given architecture to determine the extent to which margins tradeoffs affect the driving dynamics**
  - Decreasing bandwidth can increase available phase margin for more aggressive filter attenuation of parasitic dynamics (slosh, flex)
  - FCS designs that favor increased phase margins (for rigid body or slosh) can reduce aerodynamic and flex margins
  - Reduction in nominal aerodynamic stability margins can result in increased error tracking performance and control overshoot even if dispersed aero margins meet dispersed stability margins guidelines
  - Gain stabilization of low damping slosh can attenuate amplitude of forced "limit cycle" response
  - Lowering phase stable flex mode gains → lower active damping → increased loads response
  - Consequences of margin trades can vary as a function of flight condition/time
- **Parameter adjustments may reveal opportunities to improve reduced margin by trading with areas having excess margin, lower sensitivity, or lower consequence**

Flight control design alternatives may be able to restore margins that do not meet the design criteria by trading margins in other areas.

Conclusions

- NESC perspective for crewed spaceflight: **Acceptance of flight control gain/phase stability margin reductions from industry-standards should be accompanied by an adequately extensive technical treatment, including:**
  - Analyzing **fundamental physics** involved, with applicable simulation tool verification (particularly if results are dissimilar among rules of thumb, linear tools, nonlinear analysis, and flight data)
  - **Conducting sensitivity studies** in time and frequency domain to analyze effects of possible parameter and system variations
  - Studying the effects of the **consequence of instability** associated with offending modes by running stressing cases in time domain
  - **Assessing alternative flight control designs** to demonstrate present design appropriately balances overall vehicle risk (i.e., quantitatively delineate chosen tradeoffs between various stability margins and vehicle performance in the context of risk/consequence)

Related NESC Technical Bulletins

https://www.nasa.gov/nesc/technicalbulletins/

National Aeronautics and Space Administration

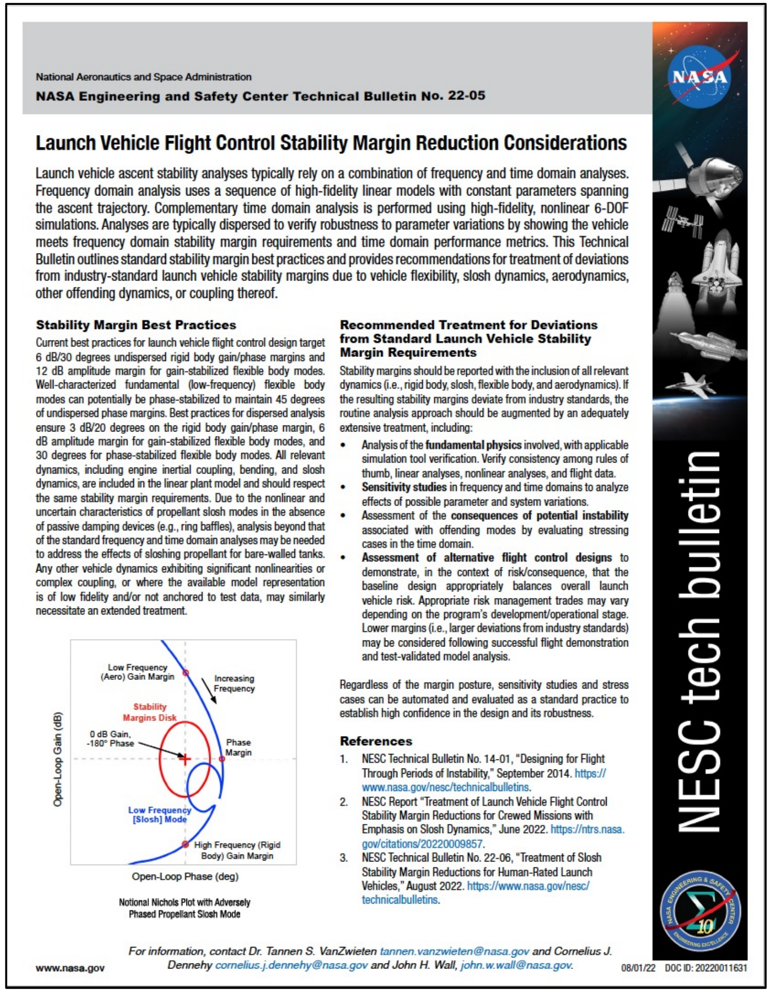
NASA Engineering and Safety Center Technical Bulletin No. 14-01

Designing for Flight Through Periods of Instability

For completeness, it is imperative that Flight Control System (FCS) designers use both complementary time and frequency domain techniques to address periods of instability. Use of standard frequency domain synthesis techniques alone may not always yield an FCS design with sufficient gain and phase stability robustness margins while simultaneously satisfying performance requirements.

NESC tech bulletin

NESC Tech Bulletin 14-01 "Designing for Flight Through Periods of Instability"



National Aeronautics and Space Administration

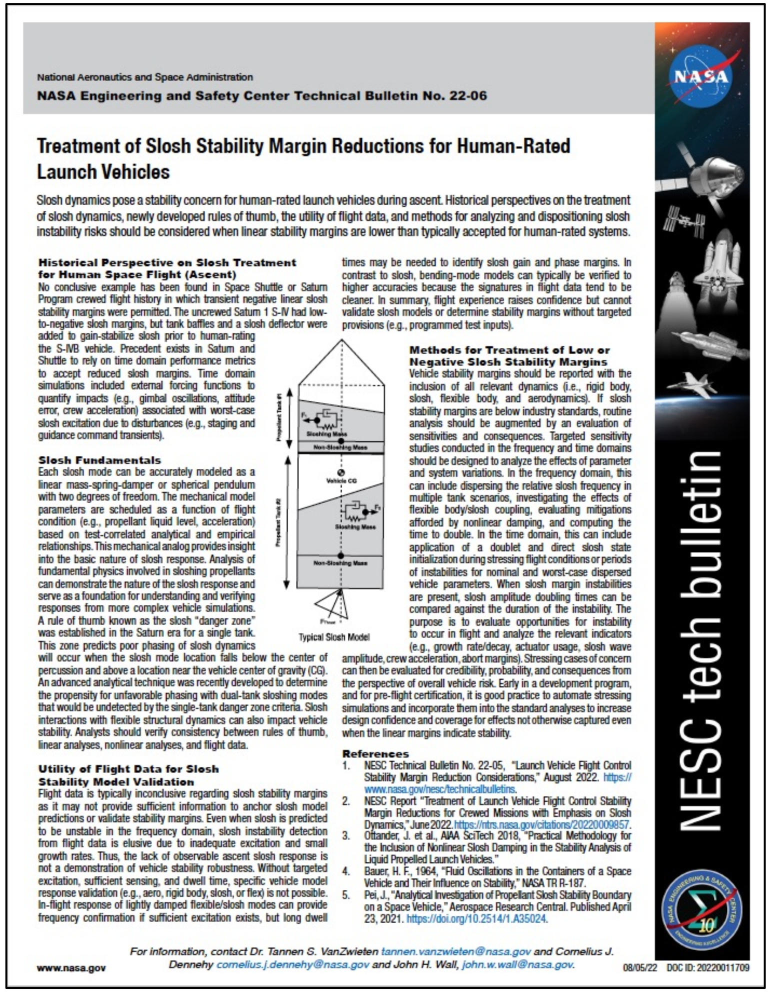
NASA Engineering and Safety Center Technical Bulletin No. 22-05

Launch Vehicle Flight Control Stability Margin Reduction Considerations

Launch vehicle ascent stability analyses typically rely on a combination of frequency and time domain analyses. Frequency domain analysis uses a sequence of high-fidelity linear models with constant parameters spanning the ascent trajectory. Complementary time domain analysis is performed using high-fidelity, nonlinear 6-DOF simulations. Analyses are typically dispersed to verify robustness to parameter variations by showing the vehicle meets frequency domain stability margin requirements and time domain performance metrics. This Technical Bulletin outlines standard stability margin best practices and provides recommendations for treatment of deviations from industry-standard launch vehicle stability margins due to vehicle flexibility, slosh dynamics, aerodynamics, other offending dynamics, or coupling thereof.

NESC tech bulletin

NESC Tech Bulletin 22-05 "Launch Vehicle Flight Control Stability Margin Reduction Considerations"



National Aeronautics and Space Administration

NASA Engineering and Safety Center Technical Bulletin No. 22-06

Treatment of Slosh Stability Margin Reductions for Human-Rated Launch Vehicles

Slosh dynamics pose a stability concern for human-rated launch vehicles during ascent. Historical perspectives on the treatment of slosh dynamics, newly developed rules of thumb, the utility of flight data, and methods for analyzing and dispositioning slosh instability risks should be considered when linear stability margins are lower than typically accepted for human-rated systems.

NESC tech bulletin

NESC Tech Bulletin 22-06 "Treatment of Slosh Stability Margin Reductions for Human-Rated Launch Vehicles"

BACKUP

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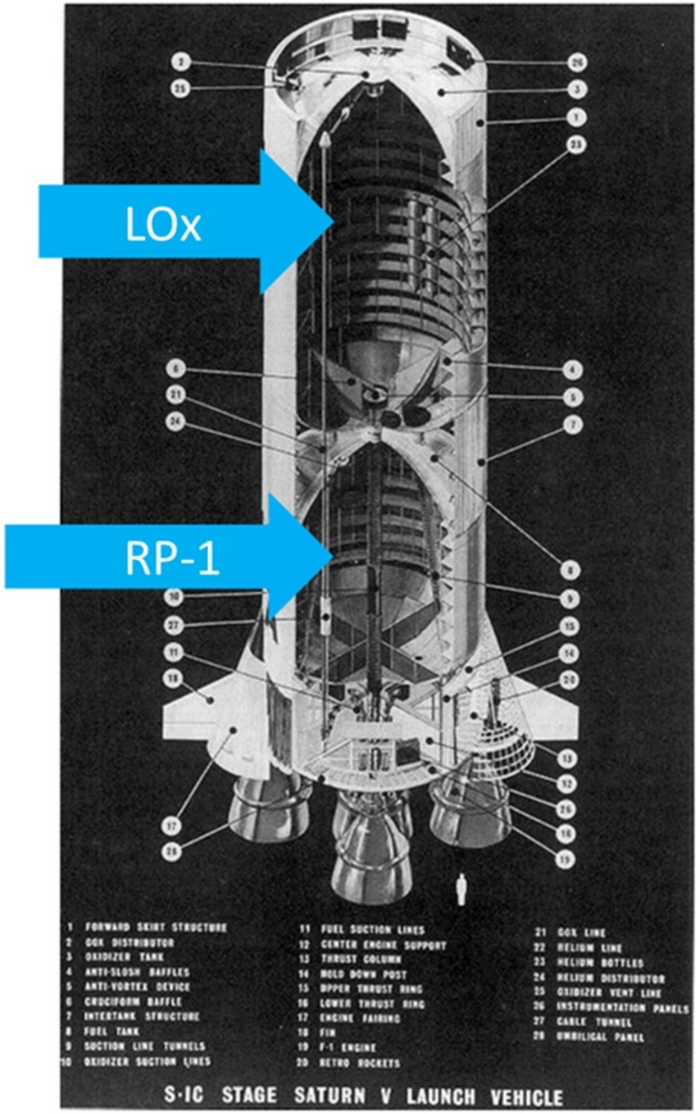
Historical Perspective

Slosh Treatment for Human Spaceflight (Ascent Stability)

- **No conclusive example found in Shuttle and Saturn crewed flight history where slosh instabilities were allowed**
  - The unmanned Saturn 1 S-IV had low, even negative, LH_2 slosh margins; however, tank baffles (and a slosh deflector) were added to gain-stabilize slosh prior to human-rating the S-IVB vehicle
- **Precedent exists in Saturn and Shuttle to use time-domain performance metrics to allow reduced slosh margins**
  - Time-domain simulations included external forcing functions to bound worst-case slosh excitation due to transient disturbances, e.g., staging, guidance transitions
  - Limits on "slosh-induced" limit cycle oscillations from external forcing functions:
    - Shuttle: limited attitude error, crew linear (g) acceleration
    - Saturn examined bounds on engine gimbal oscillations

Human spaceflight launch vehicle propellant slosh has historically been stabilized (i.e., ascent vehicles for crewed spaceflight never flown with negative slosh margins).

Rigid-body phase margins for human spaceflight have been maintained at 30 degrees or more (non-dispersed).



List of relevant historical references provided in backup

Time-Domain Response Indicators

- **Largest excitation/response should be evaluated under worst-case stressing conditions and slosh parameters to ensure that:**
  - Direct slosh initialization with large magnitudes does not affect vehicle system (no crew accel limits, TVC concerns, or significant vehicle motion)
  - Doublet required to produce such large magnitudes would cause abort due to rigid body response prior to exceeding load limits
  - Monte Carlo with worst-case conditions and direct slosh initialization would be in family with nominal slosh initialization predictions
  - Large slosh angles are not expected to be an issue for propellant thermal management or loads on the tank structure/baffles

Thrust Vector Control (TVC) Considerations

- **TVC nonlinearities, especially those that affect low frequency, can potentially interact with slosh dynamics**
- **Flight control analysis can predict whether LCOs are driven by TVC response nonlinearities (e.g., gimbal friction) or slosh nonlinearities (damping dependence on wave height)**
  - If LCO is defined by TVC and not slosh, then there will be a TVC limit cycle before magnitudes increase to produce slosh responses at the LTI-assumed slosh wave height

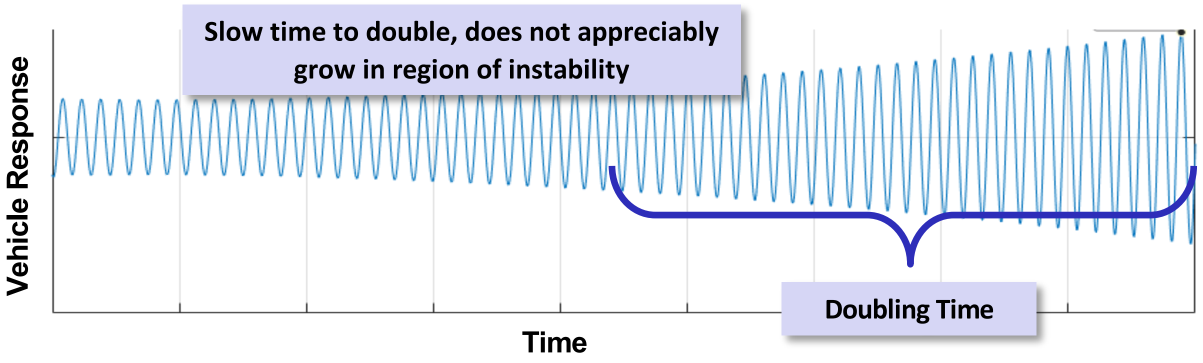
Assessment of launch vehicle response in the presence of forced excitation of slosh instability can reveal which subsystem is limiting. For example, the doublet required to produce large-magnitude sloshing motion may trigger an abort due to the rigid-body response before appreciable slosh-induced control response is observed in the TVC command.

Fundamental Physics Can Enable Understanding and Mitigation of Apparent Time/Frequency Discrepancy

Low damping slosh modes can exhibit very slow time to double, and therefore may not exhibit appreciable growth during the unstable region of flight.

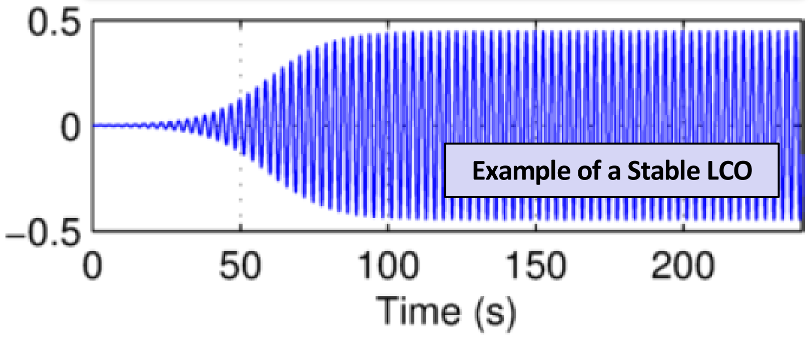
- **Unbaffled booster tanks exhibit low damping with little dependence on wave amplitude**
  - For baffled tanks, damping increases with wave amplitude resulting in a bounded, small-amplitude LCO

Low damping slosh modes, once excited, can quickly reach a near-constant amplitude response resembling an LCO in the period of flight of interest.



- **Unbaffled slosh immediately responds with a near-constant amplitude oscillation that is proportional to its excitation source**
  - Stabilization of near-zero damping slosh mode via flight control modifications reduces the amplitude, but does not appreciably alter negligible growth rate or decay
  - <u>Key questions for analyst:</u>
    - *What is the maximum acceptable slosh amplitude?*
    - *What is the largest source of slosh excitation?*

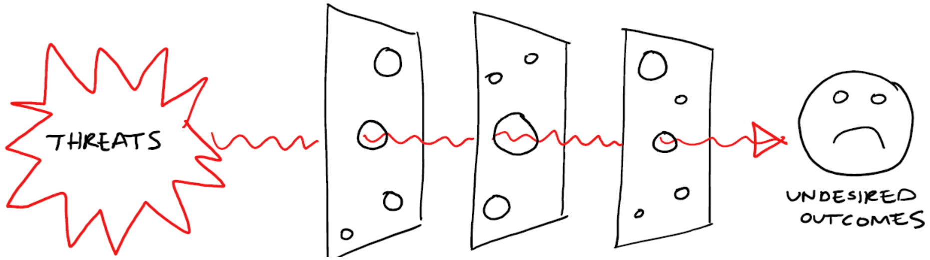
Forced response rise time can be significantly faster for low damping modes (e.g., unbaffled slosh)



A *limit cycle oscillation (LCO)* is a stable, periodic oscillation characterized by a bounded amplitude and constant first harmonic frequency, determined by the nonlinear properties of the system

Failure to Meet Stability Margin Design Criteria: Implications

- **All launch vehicle flight control instabilities are not equal in their consequence**
  - For low damping modes (e.g., unbaffled slosh), a gradual increase in “limit cycle” amplitude occurs when the open loop reaches instability
  - For high damping modes (rigid body, high gain flex modes), the gain perturbation required to reach instability is greater, but the vehicle will exhibit a rapidly divergent response
- **Margin reductions can be acceptable when accompanied by a full body of technical justification**
  - However, maintain awareness that stress cases cannot exercise “unknown unknowns” that are key links in the accident chains leading to many flight anomalies/failures
  - Stability margins guard against unforeseen/unexpected conditions



Autopilot stress cases that are consistent with best practices for evaluation of robustness are unable to exercise “unknown unknowns” (i.e., stability margins guard against unforeseen/unexpected conditions).

Evaluation of Flight Control Stabilization Trades

Additional Remarks

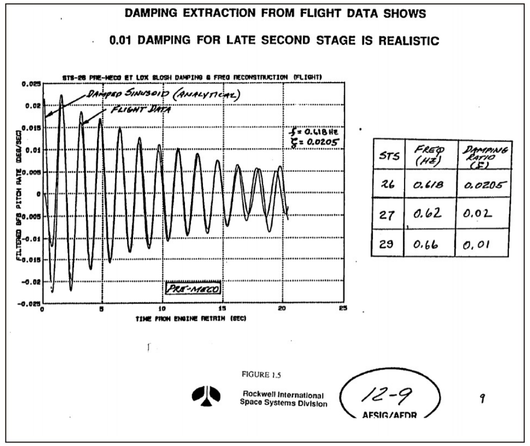
- For cases in which stability margin expectations are not being met, best practices seek to **demonstrate specifically what is being traded** in terms of margin allocation and performance loss/gain.
- **Specific vehicle configurations may require additional margins in specific areas of sensitivity** (e.g., aerodynamic uncertainty and consequence of high aero loading) and can be traded against lower risk margin degradation (slosh and rigid body phase margins).
- Restoring an unstable system to stability will incur less margin trade penalty than achieving full margins.
  - Margin trades should be informed by the consequences associated with the modes in question.
- Appropriate **management of trades pertaining to margin reductions may vary depending on when in a program's history they occur.**
  - Lower margins (larger reductions) may be permissible following successful flight experience if post-flight mission analysis has allowed for validation of the models impacting the margin reductions in question.
  - Note that the utility of flight data with respect to validating slosh models may be minimal (see F-13).
- Early in the launch vehicle certification process, provider should **present full justification when advocating for reduced stability margins in the context of the overall vehicle risk**. Following sufficient justification of margin reductions, tailored requirements can alleviate an unnecessary resource burden in subsequent analysis cycles for a specific vehicle configuration.

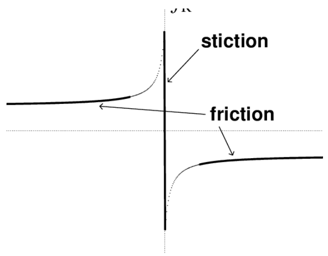
Impact of Actuator and Sensor Nonlinearities During Quiescent Flight

Stiction in TVC actuators or equivalent effects can decouple the controller from propellant slosh effects (i.e., mask small-amplitude time-domain instabilities) during quiescent regions of flight until slosh amplitudes are large enough to induce motion.

- **Open-loop slosh response due to TVC stiction used by STS during exoatmospheric flight to validate slosh models**

Reference: Altenbach, R. et al., Space Shuttle Ascent FCS Historical Data Recovery Document, SSD94D0286, Rockwell International Space Systems Division, September 30, 1994





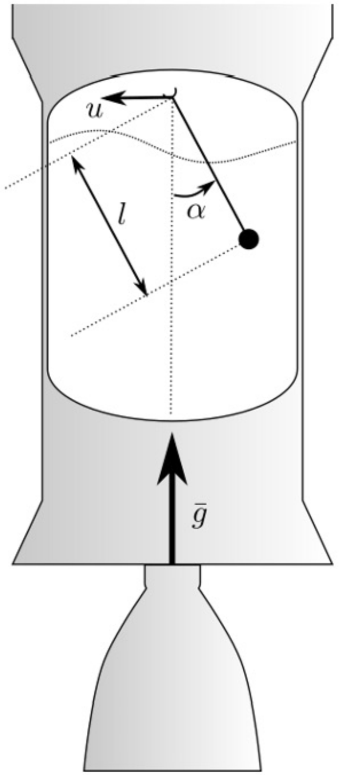
STS slosh damping flight test validation possible due to high quality rate gyros and presence of RS-25 gimbal bearing stiction

- **If slosh instability occurs during boost phase near max-Q, atmospheric disturbance can mitigate the need to investigate the impact of these nonlinear effects**
- **Such a condition could occur with unstable slosh in a quiescent flight regime**
  - **Nonlinearities could mask a time-domain instability in repeated nominal flights**
  - **Anomaly could force larger amplitude motion, which excites the FCS and thus the slosh instability**

Aerodynamic disturbances + Boosters =

(For Rockets)

Limited Treatment of Rotary Slosh



"Nonlinear Models for Rotary Sloshing Dynamics," J. Orr, April 2020

- Lateral sloshing energy can transition to rotational motion and/or rotary slosh, but no specific reason has been identified suggesting that rotary slosh is a concern for this vehicle
- Rotary slosh stressing cases can be evaluated in the time domain using a spherical pendulum slosh model with direct slosh initialization
- Bauer model investigated as a possible nonlinear rotary slosh model (more conservative than current model); limited nonlinear rotary slosh modeling and testing data exists (ref. 1)
- Forward work on rotary slosh modeling supported as a discipline-advancing activity under the NESC GN&C TDT

An unbaffled, unstable slosh mode carries inherent risk due to its lack of mechanism for energy dissipation, and there is greater opportunity for lateral energy to transition to rotary slosh.

Alternative models to the spherical pendulum model are available, with limited modeling and test data, that better predict rotary motion used in nonlinear time-domain analysis to complete an evaluation of the expected behavior.